MOLECULAR CLOUDS IN ORION AND MONOCEROS

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ABSTRACT: A 1.2-meter millimeter-wave telescope has been used to survey CO in the constellations of Orion and Monoceros. Many new molecular clouds have been found. The distribution of molecular material shows two striking characteristics: 1) Most of the molecular clouds in this region appear to be connected by continuous extensions and filaments. To judge from continuity in radial velocity, most of these connections appear to be real, and are not merely the result of projection along the line of sight. 2) There are at least two slender filamentary features longer than 10° in angular extent. These filaments may connect the molecular clouds lying well out of the Galactic plane to clouds lying in the plane. Their shape and orientation suggest that magnetic fields may play a role in their evolution. The observed velocity gradients may be explained by accelerated gas flow along the filament.

Previous CO studies of molecular clouds in the second and third galactic quadrants focussed on optically prominent regions containing clear examples of star formation. These studies revealed the presence of a number of quite discrete objects having maximum diameters of about 100 pc and masses on the order of $10^5 M_\odot$ (Kutner et al. 1977, Lada et al. 1978, Blitz 1978).

Do such objects exist which are not accompanied by star formation? The clear bias in the early CO observations towards H II regions and infrared sources meant that very little light was shed on this interesting question.

Here we report the results of a survey of CO at negative galactic latitudes mainly in Orion and Monoceros, which greatly extends the spatial coverage of prior surveys. Several new features emerge, the most striking of which are very long (10-20°) molecular filaments which appear to connect molecular clouds lying far below the galactic plane to molecular features in the plane itself. In addition, many new clouds covering a large range of sizes have been found.

B. H. Andrew (ed.), Interstellar Molecules, 197–203.

The observations were made with a 4-foot millimeter-wave telescope at Columbia University, which has a beamwidth of 8 arc minutes at the frequency of the $J = 1 \rightarrow 0$ CO line. Spectra of CO were taken at over 5000 positions. Corresponding observations of ^{13}CO have not yet been made, so mass estimates for the molecular objects described here are not yet available. We report here only the main findings of the spatial distribution and kinematics of CO.

Maps of peak intensity of CO emission are presented in figures 1 and 2 which together cover about 300 square degrees of sky. The sampling is fairly complete in these regions, and the major molecular features have probably all been found. The extent of molecular gas in these regions is clearly very great. Molecular emission in figure 1 extends from the Orion A and Orion B clouds in Orion's Sword observed by Kutner et al. (1977) north almost to Betelgeuse ($\alpha = 5^h52.5^m$, $\delta = +7\overset{\circ}{.}4$), and from there east almost to the molecular cloud observed by Blitz (1978) associated with the Rosette nebula (just off fig. 1 to the east). Figure 2 shows the southern portion of the survey, excluding the southeastern extension of the Orion A cloud, for which $V_{LSR} <$ 8 km s^{-1}. The filamentary structure on the right in figure 2 actually overlaps the Orion A cloud along the line of sight at $\alpha = 5^h35^m - 5^h45^m$, but the two are clearly separated in velocity and hence may not be physically connected. CO emission is nearly continuous from the direction of the Orion A cloud ($b = -19°$) to the CMa OB1 molecular clouds lying in the galactic plane (Blitz 1978). Contained in the CO complex in figure 2 is the large Mon R2 molecular cloud, the central part of which was previously studied by Kutner and Tucker (1975) and by Loren (1977).

Large Molecular Filaments

Two large features with unprecedented filamentary structures are apparent in CO. They lie at $\delta \sim 5°$ and $\delta \sim -10°$ and are approximately parallel to the celestial equator and to each other. Both intersect the galactic plane at a large angle (~50°). On the Palomar Sky Survey these large-scale molecular filaments can be partially discerned as a sequence of very diffuse patches; with a small amount of additional foreground extinction they would be virtually invisible. The two features have many other remarkable points in common:

1) They are both quite long -- 12° for the one at $\delta \sim 5°$ and 22° for the one at $\delta \sim -10°$ (if it is indeed a single continuous structure). Curiously, their projected separation is about equal to their projected lengths.

2) Relative to their lengths, they are very narrow -- only 15 to 30 arc minutes between one-half peak intensity contours. This continuous and extreme narrowness means that these objects are almost undoubtedly true filaments, and not thin disk-like clouds seen edge-on.

3) Line widths are large in the filaments (4-8 km s^{-1}) compared to quiescent molecular clouds ($\Delta v \sim$ 1-2 km s^{-1}) in regions devoid of apparent

https://doi.org/10.1017/S0074180900072557 Published online by Cambridge University Press

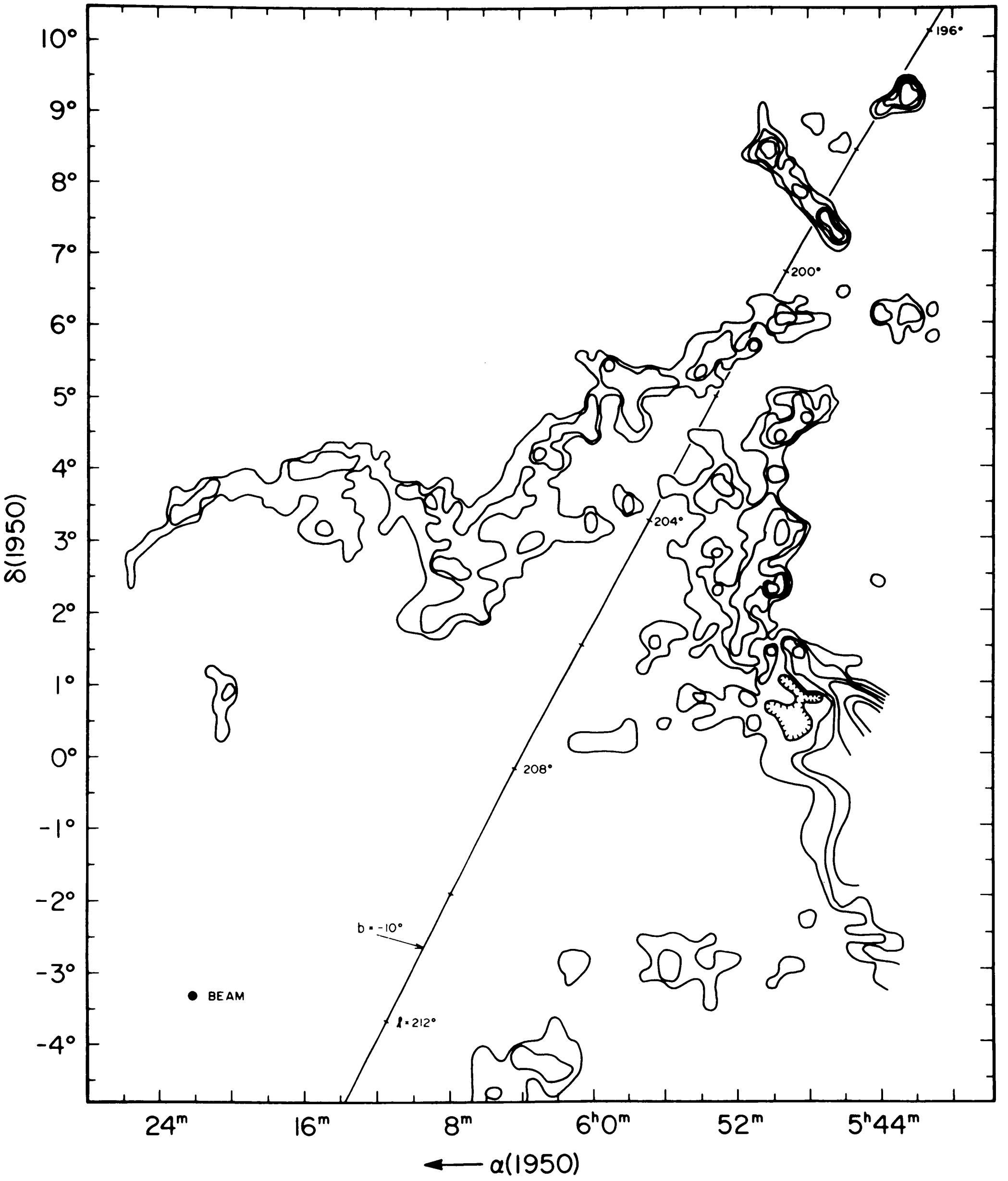

Figure 1: Contours of peak intensity of J = 1→0 CO emission in the northern portion of the survey field. Units are °K of antenna temperature corrected for atmospheric losses (the correction for telescopic losses, which amounts to a factor of ~1.7, is not included and will be dealt with in a later publication). The lowest contour and the contour interval are 1K. Galactic coordinates are indicated along the line at b = -10°.

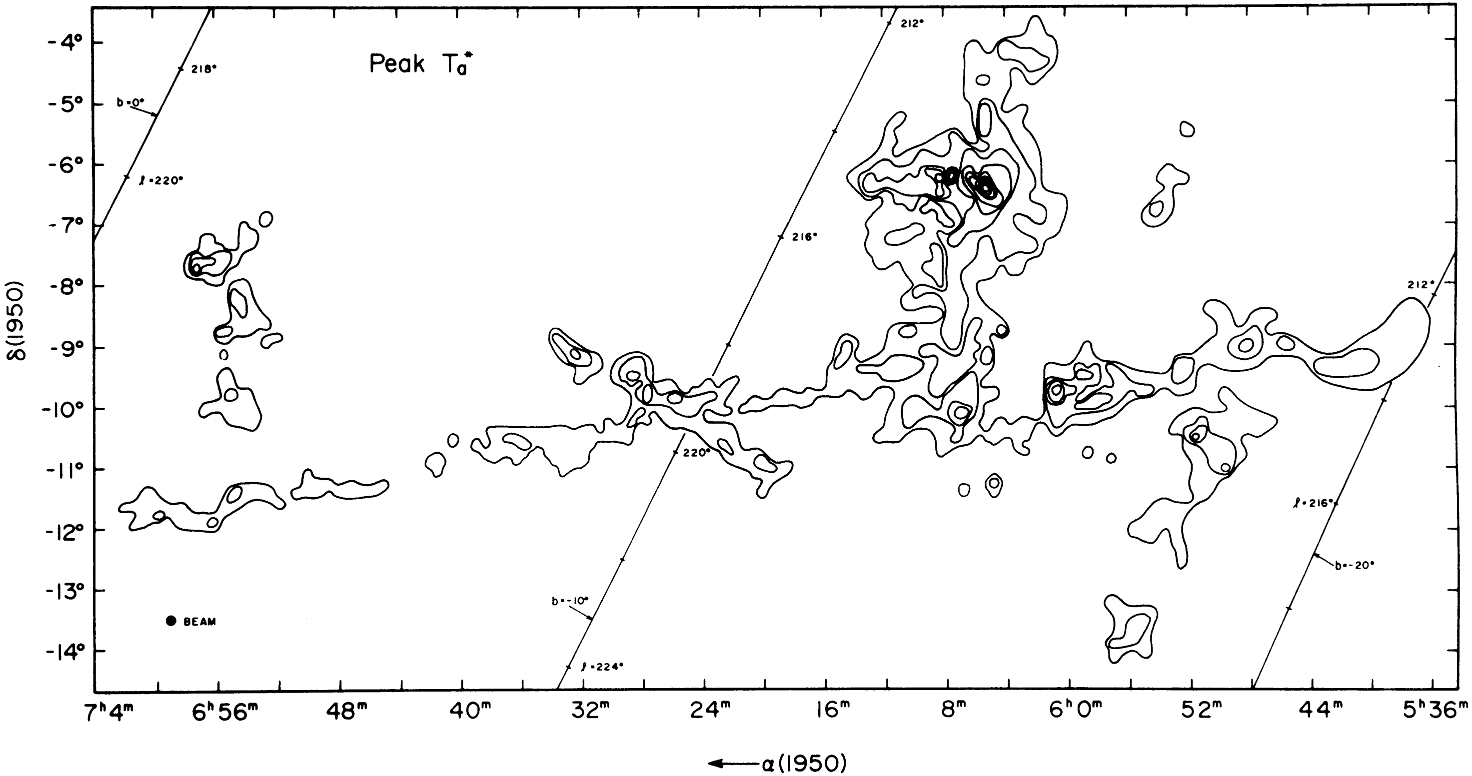

Figure 2: Contours of peak intensity of J = 1→0 CO emission in the southern portion of the survey field. Same contour values as in figure 1.

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star formation. Consequently, the central ridges of the filaments are more prominent in a map of integrated intensity than the peak intensities of figures 1 and 2. The increased line broadening does not appear to be associated with the presence of stellar sources of heat as in many large molecular clouds.

4) Velocity gradients exist along both filaments. In the northern one, gradients occur along short (3-5°) segments, and abrupt velocity discontinuities sometimes occur where two such segments overlap. The southern filament is similar except for a more pronounced velocity gradient along a major portion of its length: between $\alpha = 6^h18^m$ and 6^h52^m the velocity changes monotonically from ~8 to ~18 km s^{-1}. Because these filaments are unlikely to be rotating around an axis perpendicular to their length, it is tempting to interpret the velocity field in terms of flow along the filament. If there is a flow along the filament, the gradient may reflect either a changing orientation of the filament with respect to the line of sight as one proceeds along the cloud, or an acceleration of the flow.

The shape and motion of these filaments suggest to us the influence of a magnetic field which is highly ordered on a large scale. The filaments can be interpreted as magnetic flux tubes along which the gas is constrained to flow, although the fattening of the filament at places where the observed velocities are relatively complex suggests that there may exist pools along the filament in which the field orientation and gas motions are relatively chaotic. It is natural to suppose that the direction of flow is from the Orion region towards the plane, but we have as yet no way of proving this. The local scale height for young objects (e.g., OB stars) is about 50 pc, and it is reasonable to assume that this figure holds for molecular clouds as well (at 5 kpc from the galactic center the scale height for molecular clouds is known to be ~50 pc [Cohen and Thaddeus 1977]). Therefore, almost all the CO observed in this study is farther from the galactic plane than a molecular scale height. The gravitational force of the galaxy at such distances is sufficient to provoke an inflow of molecular gas.

The history and structure of the Orion region as a whole have long posed a number of interesting and difficult problems. What has been responsible for elevating so much material -- a mass probably in excess of $10^6 M_\odot$ -- so far above the plane? And what keeps it there?

By suggesting an exchange of matter with the plane along large scale magnetic filaments, the CO data presented here may provide important clues towards resolving these questions.

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DISCUSSION FOLLOWING MORRIS

Blitz: Using a best guess for the distance to the filaments, can you estimate the mass and mean density of the filamentary structure?

Morris: Lack of ^{13}CO observations prevents me from making a reliable estimate of the masses or densities. They are conceivably much smaller than in the giant molecular clouds.

Churchwell: The Orion filament which you showed is remarkably straight over $\sim$200 pc. Since it is almost perpendicular to the galactic plane, it is surprising that galactic rotation has not caused significant bending. Do you have any comment on this?

Morris: I am equally surprised. Perhaps one can infer that these filaments have very little extent along the direction to the galactic center.

Glassgold: What is the relation of your observations to HI studies, especially with regard to the filamentary structure?

Morris: We have taken a preliminary look at the HI studies of this region, and have found no obvious features which correspond to the filaments. Aside from the vague presence of these filaments as absorption features on the Palomar Sky Survey prints, they appear to be definable only by virtue of their CO emission.

Linke: Might there not be other CO features in the large regions of your maps which were not examined?

Morris: The sampling of the regions shown varied from 1° intervals to 1 beamwidth spacing. Most clouds greater than 20'-30' in extent have probably been found.

Crutcher: Is there any information available from optical polarization studies about the possible alignment of the interstellar magnetic field with the molecular filaments?

Morris: The polarization has been measured for only five or six stars in the direction of the two filaments, and these few measurements do indeed indicate a magnetic field aligned along the filament. However, more systematic optical polarization studies are needed.

Gilmore: The two long CO filaments that you showed, the one in the Orion B cloud, and the other south of the Monoceros region, were at a large angle to both the plane of Gould's Belt and the galactic plane. Furthermore, the Parker stability has a size scale of $\sim$1 kpc, not much larger than the size of Gould's Belt. What do you see as the relation of these two CO filaments to Gould's Belt? Would you consider such a large-scale order to the magnetic field at a large angle to Gould's Belt as significant or anomalous?

Morris: I think it is too early to speculate on the relation of these filaments to larger-scale structures, but they are quite provocative

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because they suggest that magnetic fields may play a significant role in the evolution of 0.1-1 kpc structures.

Sandqvist: We have analysed the local neutral hydrogen gas over the entire sky as well as many of the nearby dark clouds, and have found that these components are kinematically and spatially related to Gould's Belt of bright stars. They form a subset of Gould's Belt, we believe, that does not reach out as far as your Orion clouds, nor attain as high expansion velocities. Could you describe the relation of your clouds to the interstellar matter in Gould's Belt?

Morris: The model for the Gould's Belt system presented by Stothers and Frogel (1974, Astron. J., 79, 456) and Frogel and Stothers (1977, Astron. J., 82, 890) does extend to the distance of the Orion clouds. However the mean velocity of molecular gas in the Orion-Monoceros region, $\sim$10 km s^{-1}, is indeed higher than that usually found for Gould's Belt gas. Also, at 850 pc, the Mon R2 cloud probably lies beyond the Gould's Belt system. Therefore we have no strong evidence that the filaments are related to Gould's Belt.

Kuiper: It would seem that any external input of kinetic energy (such as by supernova, spiral arm passage, or radiation pressure from O stars) would give elongated features because of the eventual separation of faster moving material from the slower. One might avoid in this way the problem of not seeing elongated features in HI. On the other hand, if magnetic fields were to control the shape, there would be no reason not to see extended curved shocks. Do you have a reason for ruling out such streaming as the cause for the observed shapes?

Morris: Your suggestion probably applies to the cloud at $\alpha=5^h48^m$, $\delta=+8°$, which borders the HII region surrounding λ Ori. The two long filaments, however, do not appear to be arranged near any obvious sources of kinetic energy.

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